

FLYING COMPLEX APPROACHES USING A HEAD-UP DISPLAY:
EFFECTS OF VISIBILITY AND DISPLAY TYPE

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ABSTRACT

Air traffic controllers, both civil and military, will soon have the ability to direct pilots to fly complex landing approaches. The imminent replacement of the Instrument Landing System (ILS) with a landing system based on Global Positioning System (GPS) technology at major airports in the United States will allow pilots to fly landing approaches with curved segments and varying descent rates in order to avoid noise abatement areas. From a military standpoint, flying complex approaches will allow better threat avoidance and operational security. Current head-up primary flight references may be inadequate to fly these complex approaches, but the proposed alternative – a pathway-in-the-sky and/or synthetic terrain display – may involve too much clutter for a head-up display (HUD), depending on visibility conditions. This paper reports the findings of an on-going program of research in the Air Force Research Laboratory designed to create a next-generation, head-up primary flight reference that will allow pilots to fly complex approach and weapon delivery paths regardless of visibility conditions. The findings of three studies examining different head-up display formats and external visibility conditions are summarized. The conclusions drawn from these studies are that a head-up pathway-in-the-sky display will greatly improve pilots' ability to fly complex flight paths in comparison to the current military standard head-up display regardless of external visibility, and that the inclusion of synthetic terrain in the HUD will improve situation awareness in reduced visibility conditions.

INTRODUCTION

Approach navigation systems provide the guidance necessary to safely land aircraft under all weather conditions. The dominant approach system today is the Instrument Landing System (ILS), developed more than 50 years ago and adopted by the Federal Aviation Administration and the International Civil Aviation Organization in the 1940s. Many of the current ILS ground stations were installed 20 to 30 years ago, and as a result, frequency infringement, system maintenance and support have become problems. Costs are high and replacement parts are often no longer available (Hart, 1993).

The Global Navigation Satellite System, also known as the Global Positioning System (GPS), is

being developed as an alternative to the ILS (Harvey, 1997). Unlike the ILS system, which requires a straight-in approach, GPS systems will allow pilots to fly curved path approaches. With this new capability comes the question of how best to portray this information to the pilot. One idea is the pathway-in-the-sky format.

The concept of using a pathway display to assist pilots in anticipating upcoming flight paths was first formulated and defined in the early 1950s through the Army-Navy Instrumentation Program (Watler and Logan, 1981). The Navy subsequently conducted a series of pathway evaluations including flight tests (Hoover, Cronauer, and Shelly, 1985). When the issue of curved approaches arose, the pathway seemed an ideal method of depicting these complex approaches to the pilot.

This paper discusses the results of three studies that examined the utility of pathway-in-the-sky head-up display (HUD) symbology (hereafter referred to simply as Pathway) in flying complex curved paths.

METHOD

Subjects

All three studies used volunteer USAF pilots who had varying amounts of experience flying HUD-equipped military aircraft. All were male. Studies I and III had twelve participants while Study II used thirteen subject-pilots.

Apparatus

All three studies used fixed-based simulators of generic fighter aircraft with standard aircraft controls and HOTAS (Hands On Throttle And Stick) functions. Study I used a cockpit in which some pilot inputs and responses were done via programmable bezel buttons, with the simulated HUD shown on a top-mounted Cathode Ray Tube (CRT). Studies II and III used a cockpit in which pilot inputs were made via buttons on a touch-screen display with the external visual scene and superimposed HUD symbology shown on a projection screen roughly ten feet in front of the pilot. All studies included top-down map displays. Studies I and II also used a communications panel and Crew Alerting and Status System (CASS) display to implement secondary tasks and system emergencies

(see Reising, Liggett, Kustra, Snow, Hartsock, and Barry, 1998 for details).

STUDY I: MIL-STD HUD VS. PATHWAY

The first study compared the Pathway to a conventional HUD when flying a curved approach to landing in simulated Instrument Meteorological Conditions (IMC) at night.

Display Formats

Pathway HUD Format. The Pathway uses a "highway" to display the intended route of flight. The highway is made up of a string of path blocks drawn in perspective (Figure 1). "Road signs" are also used to alert pilots to profile information such as navigation points, glide slope steepness, and phase-relevant actions (e.g., decision height, gear down).

Military Standard HUD Symbology (MS-HUD).

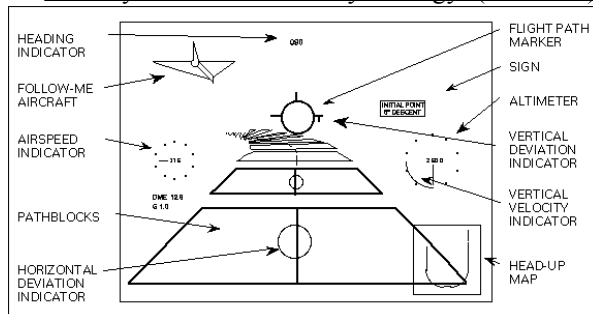


Figure 1. Pathway display used in Study I.

The MS-HUD symbology is endorsed by the USAF Flight Standards Agency as a primary flight display: no other displays are needed to fly instrument maneuvers (Figure 2). It is expected to be the baseline for all future USAF HUD-equipped aircraft. The mechanizations of individual components are similar to those of today's HUDs. However, some of the symbols in the format were changed from the "old standard". To illustrate, the airspeed indicator and altimeter have circular scales, similar to analog instruments, instead of the tape readouts used in some HUDs. Aircraft reference symbology includes a flight path marker, a climb-dive angle marker, a climb-dive scale, an acceleration cue, and a speed worm. The format also contains attitude and instrument symbology such as a Course Deviation Indicator (CDI) to display the intended course. Additionally, it incorporates standard pitch and bank steering bar symbols, similar to those used in other HUDs and attitude director indicators (ADIs), to command flight toward the intended course and glide path. A complete description of military HUD symbology can be found in Military Standard 1787B (U.S. Department of Defense, 1996).

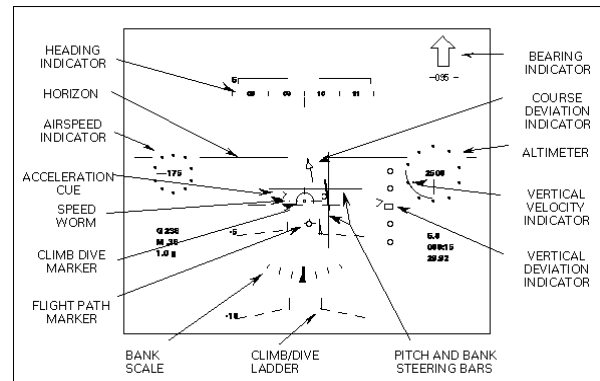


Figure 2. Military Standard HUD.

Approach Types and Disturbances

To fully explore the formats' ability to assist pilots in flying curved approaches, two of the profiles contained two turns while the other two contained four turns. Also, the steepness of glide slope and the number of changes in the degree of glide slope varied depending on the number of turns during the profile. For instance, the profiles with two turns had glide slopes of 5 and 3 degrees (simple approaches); the profiles with four turns had glide slopes of 7, 5, and 3 degrees (complex approaches).

Disturbances were either present or not present. Disturbances consisted of wind gusts, simulated emergency conditions, and simulated frequency changes. The latter two types of disturbance were termed secondary tasks because they required the pilot to perform additional duties other than flying the aircraft. Haskell and Wickens (1993) have reported that to determine differences in display formats, it is not enough to fly the displays using only wind gusts. The addition of secondary tasks, where pilots were forced to look head down for a period of time, allowed differences between the formats to emerge.

Experimental Design

Study I employed a 2 x 2 full-factorial repeated-measures design. There were two HUD formats: Pathway HUD format and MS-HUD symbology, and two levels of approach complexity: simple and complex. The order of display format presentation was counterbalanced and all profiles were flown with one HUD format before going on to the next HUD format. The order of profile presentation within the HUD format was also counterbalanced. Data were analyzed separately for conditions including disturbances. The dependent flight performance measures consisted of: root mean square (RMS) course deviations, RMS altitude deviations, and RMS airspeed deviations. Subject-pilots completed a questionnaire after each profile was flown. This questionnaire asked pilots to

rank order the flight display formats on preference and provided them an opportunity to comment on the formats.

Procedure

Pilots received training in both the classroom and in the cockpit. Classroom training included a briefing on the purpose of the study, description of the different formats, and instruction in handling of emergency and frequency change tasks. Cockpit training consisted of cockpit familiarization and flying two practice flight profiles. Each pilot flew four unique profiles with each HUD format. A paper approach plate of each profile was provided to the pilots for use during the approach.

Results

Statistical analysis using Analysis of Variance revealed that pilots had more accurate flight performance when flying the Pathway HUD format than the MS-HUD symbology (see Reising, Liggett, Solz, and Hartsock, 1995 for details). The results for disturbance data showed that, again, pilots had more accurate flight performance when flying the Pathway HUD format than the MS-HUD symbology. RMS error in maintaining commanded airspeed, altitude, and heading with the Pathway was roughly half that when using the MS-HUD.

Discussion

Pilots reported that the primary reason for the advantage of flying the Pathway HUD format over the MS-HUD symbology was their ability to see the route in the form of a highway from their present position to a point 45 seconds into the future. This advantage has also been shown when a "tunnel in the sky" head-down display is used to fly complex curved approaches (Regal and Whittington, 1995; Theunissen and Mulder, 1995). The MS-HUD symbology employed conventional navigation procedures and symbology. Raw data indicators were used to show deviations from a planned or selected route while pitch and bank steering bars indicated flight director commands to return to or maintain a given course. This format depicts the position of the aircraft in relation to the desired route in real time only. Pilots cannot "see into the future" using this format as they can with the Pathway. Pilots remarked that they were able to maintain situational awareness using the MS-HUD symbology only by monitoring the moving map display or frequently referring to the approach plate. The Pathway HUD format, on the other hand, provided in one pilot's words, "instant situational awareness". All pilots preferred the Pathway HUD format to the MS-HUD symbology for flying curved approaches. When asked about today's standard IFR approaches, nine of the twelve pilots thought they would perform

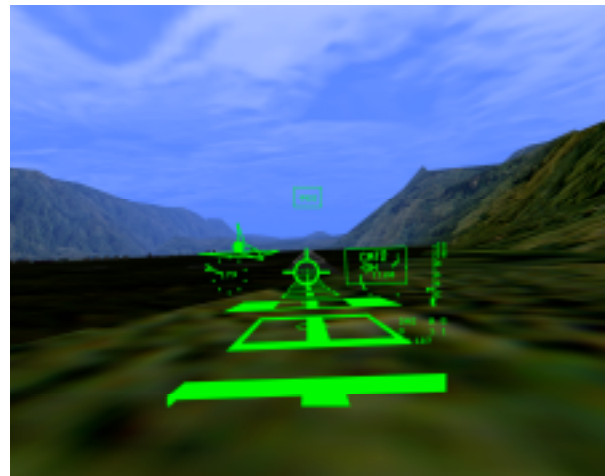
better using the Pathway HUD format over the MS-HUD symbology.

The results of Study I raised a number of questions concerning the pathway symbology's effects on flight performance in different visibility conditions. In this study the Pathway was displayed against a black background to simulate night IMC. Putting pathway symbology on the HUD results in a rather large amount of potential visual clutter. Would this symbology obscure the pilot's view in Visual Meteorological Conditions (VMC), where pilot can see the outside world clearly? Would flight performance be any different in VMC? It was hoped that the answers to these questions could be found in the results of the second study.

STUDY II: VARYING VISIBILITY CONDITIONS

Unlike most experiments, designed to look at differences among experimental conditions, the second experiment was designed to see if performance in degraded visibility conditions was equivalent to that in the clear weather case. Specifically, the experiment was designed to test for **equivalent** performance across three visibility conditions. The focus of this study was to evaluate the effectiveness of the Pathway HUD symbology to assist in executing a complex instrument approach under three different visibility conditions. The three visibility conditions tested were: 1) clear (VMC), 2) partial IMC and 3) full IMC.

Experimental Design



from commanded airspeed as well as lateral and longitudinal deviations from the desired touchdown point. RMS course deviations, RMS altitude deviations, and other flight performance measures were taken, but a discussion of those measures and results is beyond the scope of this paper. Subject pilots also completed a questionnaire after each profile was flown.

Procedure

Pilots received training in both the classroom and in the cockpit. The classroom training was similar to that in Study I. During the cockpit training, a practice approach was flown once in its entirety under the VMC condition. Pilots then flew portions of the practice approach in the two other visibility conditions. During the practice flights, subject pilots were shown an area on the runway representing an ideal landing. This ideal landing spot was on the pavement centerline, 1600 feet from the runway threshold. Data were collected on one profile for each visibility condition.

Results

One of the goals of this research was to determine if landing performance using the pathway symbology was functionally equivalent regardless of weather condition – if pilots could fly the pathway symbology just as well in IMC conditions as in VMC conditions. To discern this, confidence intervals were calculated to test whether performance in the two IMC conditions was practically equivalent to performance in the VMC condition. This approach is the same advocated by Rogers, Howard, and Vessey (1993) and promulgated by the Food and Drug Administration (1997) for testing pharmaceutical bioequivalence (e.g., testing the equivalence of a generic and brand-name of aspirin).

Based upon the opinions of subject-matter experts, aircraft type, and established Air Force training and check-ride standards, levels of practically-significant difference were set for each performance measure. These values were Lateral Error at Touchdown ± 50 feet, Longitudinal Error at Touchdown ± 500 feet, and RMS Airspeed Error ± 10 knots. Performance in an IMC condition was judged to be functionally equivalent to performance in the VMC condition if the difference between the two fell within the limits of the practically significant difference ranges. This difference was tested using confidence intervals. These confidence intervals for the three measures indicated that there were no practical differences ($p > 0.05$) between performance in the VMC condition and performance in the IMC conditions (see Reising, Liggett, Kustra, Snow, Hartsock, and Barry, 1998 for details).

Discussion

Equivalency analyses showed that pilots using the Pathway were able to land within the same dispersion pattern and maintain commanded airspeed regardless of weather conditions. One of the keys to this performance may be the information that the path provides to the pilots on final approach. In addition to the "road signs", which provide them key information

relative to their progress toward landing (e.g., missed approach point), the path itself was designed to reinforce this information. Specifically, the path block at each crucial information point was drawn with wider edges than normal path blocks. The pilots' comments revealed that the various features were easily distinguishable and logically placed.

STUDY III: PATHWAY & SYNTHETIC TERRAIN

The purpose of this study was to again test the utility of the Pathway display in flying complex paths, but this time in the somewhat more challenging scenario of a low-level, high-speed ingress to a target. Further, three synthetic terrain formats were tested for possible benefits in performance and situation awareness (SA). Synthetic terrain was added and situation awareness measured partly because of concerns (based on pilot feedback in the previous two studies and other research by Olmos, Liang, and Wickens, 1997), that a Pathway display, while increasing awareness and performance regarding maintenance of the commanded flight path, might decrease global SA, or awareness of events *other* than the commanded flight path. Should the pilot be forced from the Pathway for any reason (e.g., due to enemy threat, atmospheric phenomena, birds, or avoidance of other air traffic), decreased SA concerning elements other than the commanded flight path could prove disastrous.

Experimental Design

The study employed a 2 x 4 x 2 mixed-factors design. Visibility (IMC Night vs. IMC Day) and synthetic terrain format (grid, partial grid, texture map, or none) were within-subject variables, while the use of SAGAT questions (Endsley, 1995) was a between-subjects variable. Figure 4 shows the Pathway with grid format synthetic terrain. In addition to the RMS error values collected in the previous studies, SA was

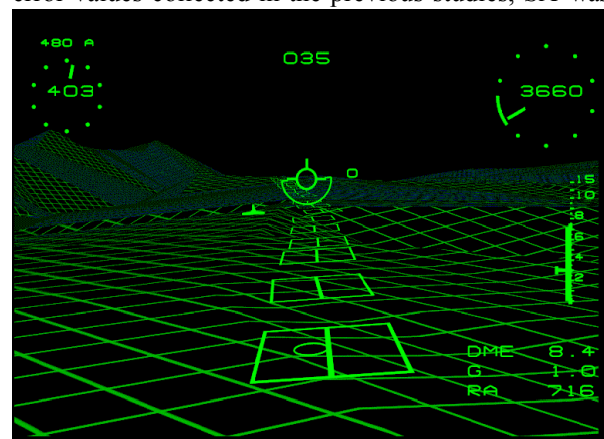


Figure 4. Pathway display used in Study III.

measured. All subjects completed an SA-SWORD

evaluation (Vidulich and Hughes, 1991) at the end of each experimental session as a subjective measure of SA. Additionally, half the subjects were asked SA questions twice during each ingress (once on-path and once off-path) using the SAGAT technique to gauge SA objectively.

Procedure

Twelve pilots volunteered to participate in this study. Subjects were required to have experience in a HUD-equipped fighter aircraft. Pilots received training in both the classroom and in the cockpit. Classroom training included a briefing on the purpose of the study, description of the ingress scenarios and different synthetic terrain formats, and instructions for responding to surface-to-air missile (SAM) alerts. Cockpit training consisted of cockpit familiarization and flying a practice flight profiles. Subjects flew a practice ingress scenario in each experimental condition prior to flying the scenario for which data were collected. Pilots flew each ingress at a commanded airspeed of 480 knots and a commanded altitude of 500 ft. above ground level. Twice during each ingress pilots were forced off-path by a SAM alert. Each ingress was concluded with loft delivery of an unguided bomb followed by an escape maneuver. Pilots completed a subjective questionnaire at the conclusion of the session.

Results

Multivariate analyses of variance revealed no statistically significant effects for any of the variables manipulated with regard to flight performance measures (i.e., RMS lateral, vertical, and airspeed deviation). Similarly, none of the independent variables affected bombing accuracy or reaction time to SAM alerts. However, large and significant main effects of synthetic terrain format and visibility were found for SA-SWORD. SA was best with the grid and texture map conditions, followed by the partial grid condition, with no synthetic terrain leading to greatly decreased SA. Overall, SA was better in the IMC Day condition than in the IMC Night condition. These effects were smaller and significant only with $p < 0.2$ with regard to overall SAGAT scores, but the pattern of results was the same. It should be noted that, because of the between-subjects design and resulting sample size in the SAGAT condition (i.e., $n = 6$), the observed power of these tests was typically less than 0.4. Responses to the subjective questionnaire indicated that eleven of the twelve pilots thought the symbology would be adequate to fly the bombing profiles.

Discussion

While objective performance measured did not differ significantly between conditions in this study, the results with respect to SA were different. Inclusion

of synthetic terrain greatly increased SA, as indicated by both subjective and objective measures. Feedback from the pilots on the subjective questionnaire reinforced these findings. All subjects thought the Pathway and Synthetic Terrain display used in this study provided better SA than a standard HUD. Interestingly, five of the twelve pilots felt that – for the purpose of flying these ingress scenarios – the pathway itself could be smaller or absent altogether and that the synthetic terrain alone would be adequate.

CONCLUSIONS

The findings of the first two studies lead to the conclusion that the Pathway is valuable in flying complex precision approaches to landing, regardless of visibility condition. The results of the third study do not contradict this conclusion, but indicate that not all pilots will find a pathway useful in all situations. It seems clear that providing the Pathway as a switchable alternative to the MS-HUD would be a useful aid to pilots at least in maintaining SA, especially if synthetic terrain is included as an additional option.

Preparation is now underway for a study that will directly compare the MS-HUD to the Pathway and Synthetic Terrain in visibility conditions not yet tested: VMC during the day, VMC at night, and IMC during the day. In addition to measures of flight performance and situation awareness, this study will incorporate workload measures in a scenario designed to severely tax pilots' information processing and attention management abilities. Upon conclusion of this study, the next logical step in this series of studies will be incorporation of the Pathway and Synthetic Terrain symbology in more realistic simulations (e.g., full-mission in a dome simulator) leading to eventual flight test.

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